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# A confirmed location in the Galactic halo for the high-velocity cloud 'chain A'

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The high-velocity clouds of atomic hydrogen, discovered about 35 years ago<sup>1,2</sup>, have velocities inconsistent with simple Galactic rotation models that generally fit the stars and gas in the Milky Way disk. Their origins and role in Galactic evolution remain poorly understood<sup>3</sup>, largely for lack of information on their distances. The high-velocity clouds might result from gas blown from the Milky Way disk into the halo by supernovae<sup>4,5</sup>, in which case they would enrich the Galaxy with heavy elements as they fall back onto the disk. Alternatively, they may consist of metal-poor gas – remnants of the era of galaxy formation<sup>2,6–8</sup>, accreted by the Galaxy and reducing its metal abundance. Or they might be truly extragalactic objects in the Local Group of galaxies<sup>7–9</sup>. Here we report a firm distance bracket for a large high-velocity cloud, Chain A, which places it in the Milky Way halo (2.5 to 7 kiloparsecs above the Galactic plane), rather than at an extragalactic distance, and constrains its gas mass to between  $10^5$  and  $2 \times 10^6$  solar masses.

Distance estimates of HVCs have long been based on models or indirect arguments<sup>2,10</sup>. The only direct method uses the presence or absence of interstellar absorption lines at the HVC's velocity in spectra of stars at different distances. Presence of absorption shows the HVC to lie in front of the star; absence places it beyond, provided the expected absorption is well above the detection limit<sup>11</sup>. Blue stars are best, since their spectra contain few confusing stellar lines. The method requires that metal ions are present in HVCs. Indeed, since suitable spectrographs have become available, CaII and other metal-ion absorption lines have been found for many HVCs<sup>3</sup> in the spectra of background quasars or Seyfert galaxies. Using HI column densities measured at high angular resolution, the metal-ion/HI ratios thus derived provide estimates of expected absorption-line strengths towards stars probing the same HVC.

The HVCs MII-MIII, for which an upper limit to the distance,  $d < 4$  kpc, is known<sup>12,13</sup>, but no lower limit<sup>13</sup>, were thus found to be Galactic, and may even lie in the Disk, as does the tiny object<sup>14,15</sup> HVC 100-7+100, with  $d < 1.2$  kpc, and distance from the plane  $|z| < 0.14$  kpc. Lower distance limits are known for Complex C<sup>16,17</sup> ( $d > 2.5$  kpc, and probably<sup>18</sup>  $d > 5$  kpc), Cloud 211 = HVC267+20+215<sup>16</sup> ( $d > 6$  kpc), parts of the AntiCenter Complexes<sup>19</sup> ( $d > 0.6$  kpc), and Complex H<sup>20</sup> ( $d > 5$  kpc). Chain A is the first HVC for which both a significant upper and a non-zero lower limit to its distance are known, constraining its location relative to the Galaxy's major components.

HVC-Complex A, also called "Chain A", was the first HVC discovered and has been studied in detail<sup>3,21</sup>. It is a 30° long filament, containing several well-aligned concentrations with velocities (relative to the local standard of rest, LSR) between  $-210$  and  $-140$  km/s. HST spectra<sup>22</sup> of the Seyfert galaxy Mark 106 show strong MgII absorption by this HVC. The fact that such absorption is not detected (it is less than 0.03 times the expected strength) in the star PG0859+593, although the HVC's HI emission (as measured at 1 arcmin resolution) is similar in both directions, sets a firm lower distance limit,  $d > 4 \pm 1$  kpc ( $z > 2.5 \pm 0.6$  kpc), for Chain A.

We have now also measured an upper limit,  $d < 10$  kpc, for the upper end of Chain A, using the RR Lyrae star AD Ursae Majoris, which lies at a distance of  $10.1 \pm 0.9$  kpc (Fig. 1). Detection of interstellar lines in the spectra of RR Lyr stars is generally hampered by the presence of many stellar lines; but these are fewer during maximum phase, when the star is hotter. Figure 2 shows portions of the spectrum of AD UMa around the CaII-H and K lines, observed during maximum, and a 21-cm profile taken in the same direction. The latter has components at velocities  $v$  (relative to the LSR) of  $-4$ ,  $-40$  and  $-158$  km/s. The CaII-K line shows the same interstellar components as the 21-cm profile, plus a strong stellar absorption around  $+70$  km/s. The weaker CaII-H line, though blended with a broad stellar H- $\epsilon$  absorption, shows similar structure. In particular, absorption by the HVC at  $v \sim -160$  km/s is present at both K and H.

Could these HVC absorptions be affected by blending with stellar lines? Figure 3 shows three FeI lines of multiplet number 4, indicating a stellar radial velocity  $v = +77 \pm 2$  km/s. Comparison of their strengths and widths with those<sup>23</sup> in the blue field-horizontal-branch star HD 161817 allows calculation (Fig. 4) of the profile of a fourth line (laboratory wavelength  $\lambda_0 = 3930.3$  Å), predicted to be present at 3931.3 Å.

Subtraction of this predicted line from the observed spectrum (Fig. 4) leaves a narrow absorption at  $v = -158.2 \pm 1.2$  km/s, in close agreement with the HVC velocity  $v = -157.6 \pm 0.2$  km/s, found at 21 cm (Fig. 2). If this absorption were due to the FeI 3930.3 Å line, it would have  $v = +96 \pm 1$  km/s in that frame, which is clearly incompatible with the stellar velocity of  $+77 \pm 2$  km/s found from the other lines in the same multiplet. The velocity difference of  $19 \pm 3$  km/s, the lack of any other suitable identification, and the agreement with the 21-cm velocity, convincingly show that the deep line at 3931.5 Å in Figures 3 and 4 must be due to CaII-K absorption at  $-158$  km/s by the HVC, while the shortward wing is due to the stellar FeI line.

The agreement in velocity of the high-velocity absorptions at K and H, and the fact that the ratio of line depths is about 2 : 1, as expected, further strengthens the identification of the HVC absorption. Thus, it is certain that Chain A lies in front of AD UMa. The CaII and HI line strengths indicate a  $\text{Ca}^+$  abundance of order 0.01 times the total solar Ca abundance, confirming our earlier<sup>11</sup> tentative result. (Note that interstellar calcium is generally strongly depleted by inclusion into dust grains, and  $\text{Ca}^+$  is not the dominant ion in the interstellar gas phase.)

The absorption seen in AD UMa sets an upper limit of  $10 \pm 1$  kpc to the distance of Chain A. Combining this with the lower limit<sup>22</sup> of  $4 \pm 1$  kpc, we conclude that the high-latitude end of Chain A lies at  $4 < d < 10$  kpc, or  $2.5 < z < 7$  kpc above the Galactic plane. Using the HI flux<sup>21</sup>, we derive an HI mass of  $9800 d^2 M_\odot$ , i.e. between  $1.5$  and  $10 \times 10^5 M_\odot$ . With the standard helium abundance, the (HI + He) gas mass would be a factor 1.4 higher. The nondetection<sup>24</sup> of CO emission from bright HI cores in Chain A implies that the  $\text{H}_2$  mass must be one or more orders of magnitude less. Recent  $\text{H}\alpha$  observations<sup>25</sup> suggest that Chain A is mostly neutral. Assuming the ionized contribution to be minor, the total gas mass in Chain A lies between  $2 \times 10^5$  and  $2 \times 10^6 M_\odot$ . The kinetic energy of the complex then is of order  $(0.3 - 3) \times 10^{53}$  erg, if we assume<sup>21</sup> a peculiar velocity,  $v_{\text{dev}}$ , of  $-130$  km/s.

Our distance bracket places Chain A definitely in the Galactic Halo, rather than in intergalactic space. It excludes models for its nature and origin requiring a distance of order 1 kpc or less, such as relationships to local molecular clouds<sup>26</sup>, or collision of an intergalactic cloud with the Galactic Disk<sup>27</sup>. It also rules out that Chain A would be a Galactic satellite at about 50 kpc distance<sup>9</sup>, or a protogalactic gas cloud at  $\sim 500$  kpc distance<sup>28</sup>, or "a member of the Local Group of galaxies", as proposed recently<sup>7</sup> for HVCs in general. Other HVCs may well be at such great distances and fit the latter model; and some, e.g. the tiny, nearby cloud HVC100-7+100 (see above), may have a local origin<sup>15</sup>.

The location of Chain A in the Halo still allows several models for its origin. For its height  $2.5 < z < 7$  kpc to be consistent with a Galactic-Fountain model<sup>4,5</sup>, a sufficiently hot halo ( $T > 5 \times 10^5$  K) would be required. The small-scale structure observed<sup>29,30</sup> in Chain A would then be due to instabilities formed in the downward flow of cooling clouds. Alternatively, Chain A may represent gas captured from intergalactic space<sup>2,6,8</sup>. In that case, collision with an ionized halo extending to high  $z$  may have served to decelerate the gas to its present velocity<sup>2,6,31</sup>, and to form the small-scale structure, which has typical time-scales<sup>3,29</sup> of order  $10^7$  years, and therefore probably formed within a few kpc of its present location. In this accretion model, the question whether the origin of Chain A lies in the Magellanic System (as debris from encounters between Milky Way and Magellanic Clouds), or far away in the Local Group (as "remnant of Local Group formation"<sup>7,8</sup>), remains open: location in the Galactic Halo does not preclude such a distant origin.

A clue to the origin of Chain A might be found in its metallicity. In a Galactic Fountain, near-solar metallicities would be expected; accretion might bring in HVCs with low metallicities. For Chain A, current information is limited to the observed column-density ratios  $N(\text{Mg}^+)/N(\text{HI}) > 0.035$  solar<sup>22</sup> and  $N(\text{Ca}^+)/N(\text{HI}) \sim 0.01$  solar (see above); in view of possible depletion by inclusion into dust grains and uncertain ionization conditions, these ratios only give lower limits to total Mg and Ca abundances. The best chance for a more significant value lies in measurement of the ultraviolet SII lines in Mark 106, since sulphur is not depleted onto grains, and  $\text{S}^+$  is the dominant ionization stage in neutral gas. Reliable metallicity values and further direct distance measurements of HVCs will hold the key to their understanding. Since the HVC phenomenon is only loosely defined, and may well include objects of very different origins, distance and metallicity measurements of various HVCs will be required.

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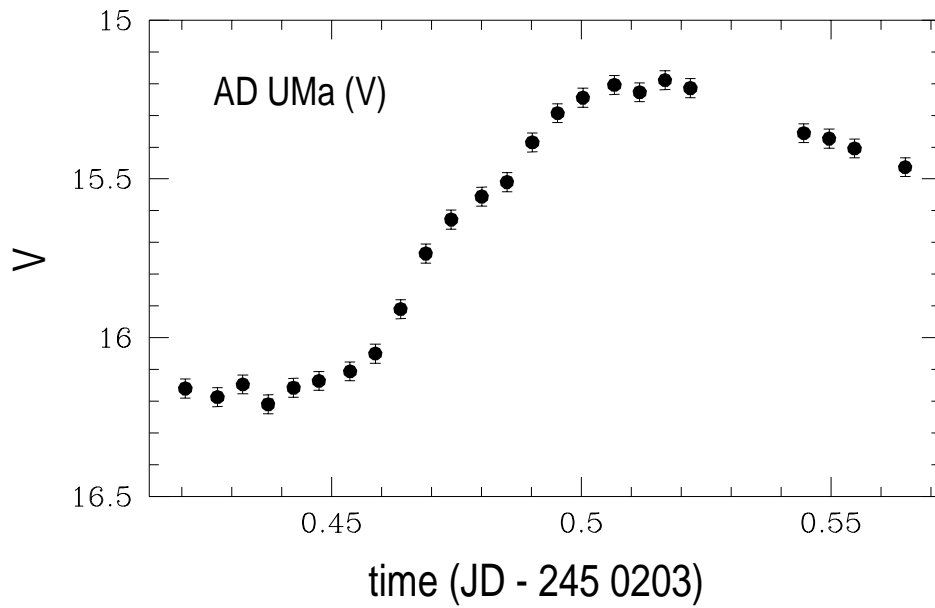


Figure 1: Partial lightcurve of the RR Lyr star AD UMa, measured in yellow light on 1996 Apr 29/30 with the Jacobus Kapteyn Telescope at the Roque de los Muchachos Observatory, La Palma TF, Spain by R.F. Peletier, H. van Woerden and D. Sprayberry. Minimum magnitude:  $16.17 \pm 0.01$ , maximum:  $15.21 \pm 0.01$ , average  $15.69 \pm 0.01$  mag. Assuming  $[\text{Fe}/\text{H}] = -1.7$  by analogy with<sup>32</sup> HD 161817, recent calibrations<sup>33,34</sup> of RR Lyr variables based on Hipparcos and other data yield an absolute magnitude  $M_V = 0.58 \pm 0.18$ . Taking an extinction<sup>35</sup> of 0.1 mag, the distance of AD UMa implied is  $10.1 \pm 0.9$  kpc. The coordinates ( $\alpha = 09^{\text{h}}23^{\text{m}}38.7^{\text{s}}$ ,  $\delta = +55^{\circ}46'33''$  (J2000);  $l = 160.40^{\circ}$ ,  $b = +43.28^{\circ}$ ) were measured from the Palomar Sky Survey, with reference to the chart in the discovery paper<sup>36</sup>; they differ considerably from those in the Moscow General Catalogue of Variable Stars.

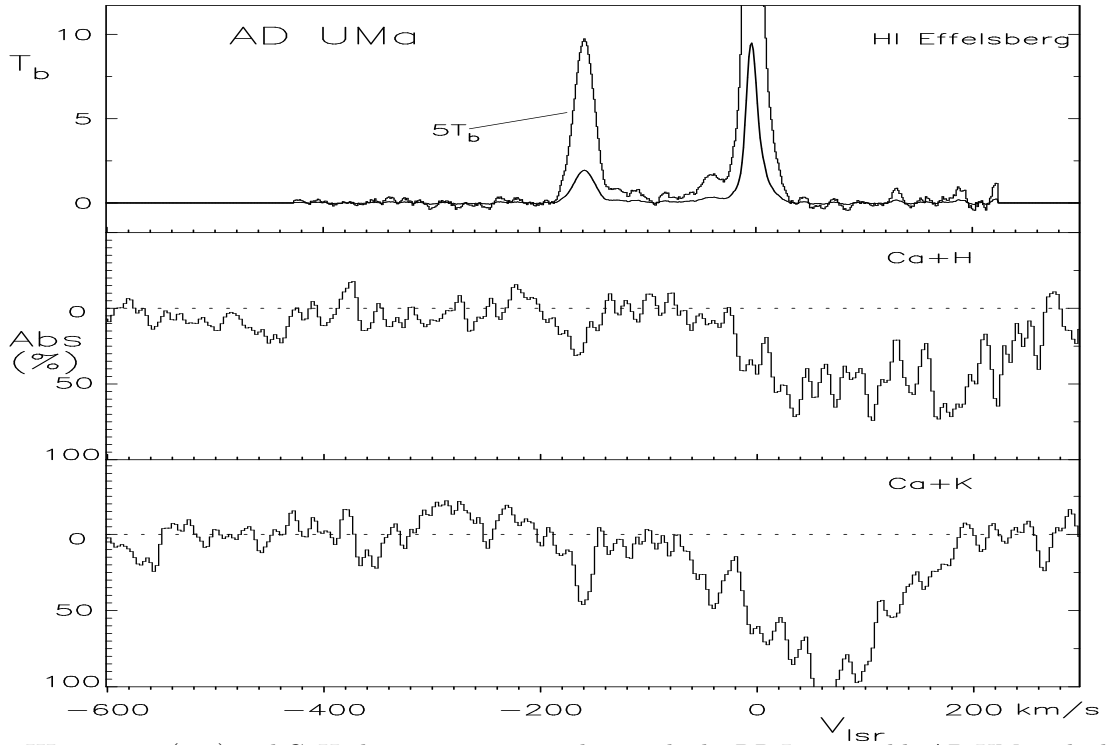


Figure 2: HI emission (top) and CaII absorption measured towards the RR Lyr variable AD UMa, which lies at 10 kpc distance, projected on HVC Chain A. The Effelsberg 21-cm profile, measured at 9' beamwidth and 2 km/s velocity resolution, is shown on two intensity scales, different by a factor 5, and has three components, at velocities (relative to the local standard of rest, LSR) of - 4, - 40 and -158 km/s; the last one is due to the HVC. The CaII H and K lines, measured with the William Herschel Telescope at La Palma at 10 km/s resolution during maximum phase on 1997 Jan 18, both show – in addition to a strong stellar component near + 70 km/s, and broad H- $\epsilon$  absorption longward of the CaII H-line – the same interstellar components as the 21-cm line. This proves that HVC Chain A, as well as the other two clouds, lies in front of the star.

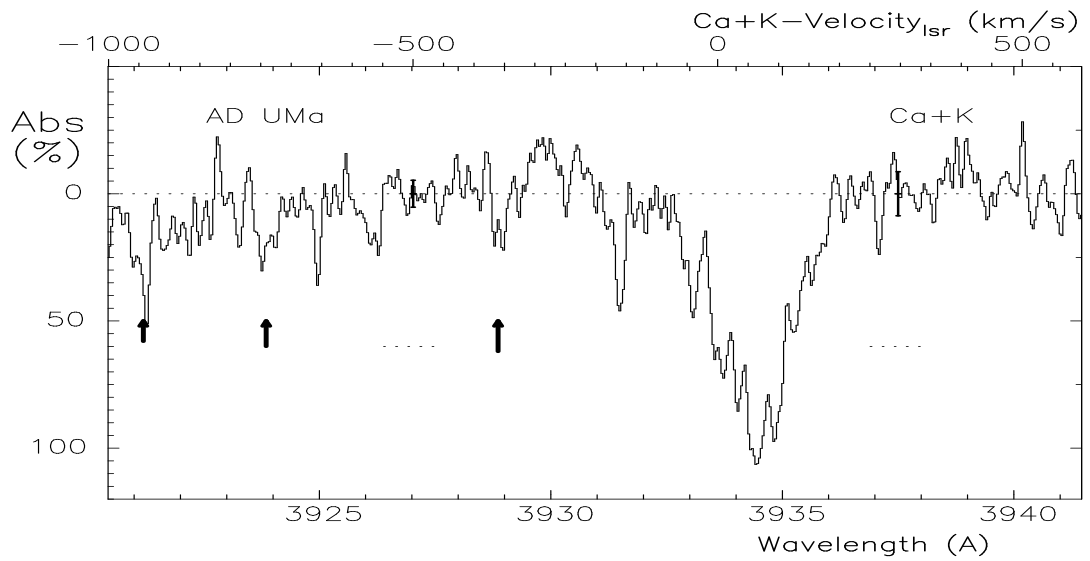


Figure 3: Spectrum of AD UMa near the CaII-K line ( $\lambda_0 = 3933.663 \text{ \AA}$ ), taken during maximum phase on 1997 Jan 18; velocity scale relative to LSR. Note the stellar K-line near  $+70 \text{ km/s}$ , and the HVC absorption at  $-160 \text{ km/s}$ . Three stellar FeI lines, with  $\lambda_0 = 3920.260, 3922.914$  and  $3927.922 \text{ \AA}$ , and shifted by about  $+1.0 \text{ \AA}$ , are indicated by arrows. Gaussian fits yield velocities  $v = +76, +74$ , and  $+81 \text{ km/s}$ . The average stellar velocity,  $+77.0 \pm 2.0 \text{ km/s}$ , is consistent with values measured for the FeI(4) line at  $3860 \text{ \AA}$  and, more coarsely, for the CaII-K and H- $\delta$  lines. For the FeI line with  $\lambda_0 = 3930.299 \text{ \AA}$  see Figure 4.



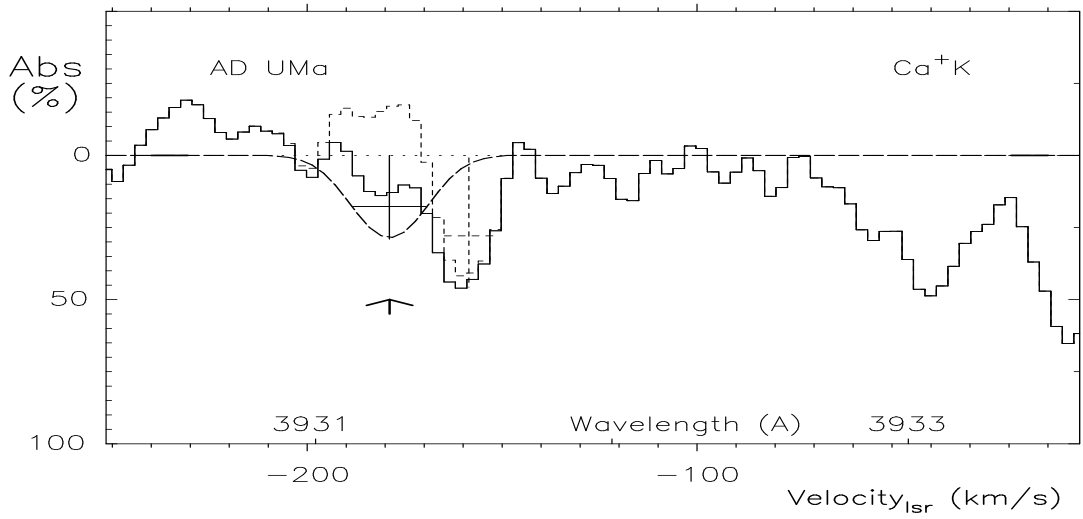


Figure 4: The predicted profile of the stellar FeI line with  $\lambda_0 = 3930.299 \text{ \AA}$  is shown by a cross and a dashed line. The observed spectrum (histogram; velocity scale given for CaII-K line), in which the continuum is clearly poorly defined, barely allows an FeI line of the predicted strength. Hence, subtraction of the predicted stellar line from the observed spectrum, leaving the short-dashed histogram spectrum, sets a lower limit to the strength of the neighbouring absorption line. This deep, narrow absorption around velocity  $-158 \text{ km/s}$  (relative to LSR), fitted with a Gaussian of  $6 \text{ km/s}$  dispersion (dashed cross), must be due to  $\text{Ca}^+$ -ions in HVC Chain A, because it is shifted by  $+19 \pm 3 \text{ km/s}$  from the predicted FeI line.

In calculating the predicted profile the following data were used: 1) the stellar velocity of  $+77 \text{ km/s}$  discussed in the caption of Figure 3; 2) the average velocity dispersion  $\sigma = 9.3 \text{ km/s}$ , found from the three FeI(4) lines with  $\lambda_0 = 3920.260, 3922.914$  and  $3927.922 \text{ \AA}$  (Figure 3); and 3) an equivalent width  $W = 90 \text{ m\AA}$ , derived from the  $W$  values measured by us for these three lines, together with the ratio of line strengths measured<sup>25</sup> in HD 161817 for the line with  $\lambda_0 = 3930.299 \text{ \AA}$  and the other three lines. The prediction procedure is supported by the fact that the line strengths found from Gaussian fits to the spectrum of AD UMa are very similar to those<sup>25</sup> in the bright field-horizontal-branch star HD 161817.